Summary of Exoplanet Forum 2008 Findings in Astrometry

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Missions For Exoplanets: 2010-2020

Highest Priority Science Topics for Astrometry

A Versatile μas astrometry mission can address them *all*!

- Survey $\sim$ 100 nearby stars for Earths
- Characterize Most Important Property: Mass
- Precurser Mission for Future Direct Imaging
- Survey $\sim$ 1000 stars for multiplanet systems
- Full planetary system architecture, geometries
- Young planet search, planetary formation

Conclusion #1: A Versatile μas astrometry mission addresses *all*!
And more...

Non-exoplanet Science

- Direct distance measurements to few $\times$ 100 kpc
- Basic properties of most/least massive stars
- Calibrate Cepheid scale for greater distances: H_o
- Black hole and Neutron star masses
- Formation/Mass Distribution/Structure/Evolution of Milky Way
- Clumpiness of dark matter
- Extragalactic Motions

PlanetHunter (Exoplanets-Only Concept): Save $\sim$ \$170-\$200M, but at a considerable price in science.

AAAC: ExoPlanet Task Force

Worlds Beyond: Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee

1 Executive summary

This is a 15 year strategy for the detection and characterization of extrasolar planets ("exoplanets") and planetary systems, requested by NASA and the NSF to the Astronomy and Astrophysics Advisory Committee. The charge to the Task Force is given in the Appendix. The strategy is an outgrowth of the efforts underway for two decades to detect and characterize extrasolar planets–in which over 260 planets and dozens of multiple planet systems have been found and studied. It is informed by a variety of technological studies within the astronomical community, industry, NASA centers and NSF-funded facilities that point the way toward techniques and approaches for detection and characterization of Earth-sized (0.5–2 times Earth's radius) and Earth-mass (0.1–10 times the mass of the Earth) planets in the solar neighborhood. The raw material for the strategy was provided in the form of invited briefings and 85 white papers received from the community.

The strategy is intended to address the following questions, given in priority order:

1. **What are the physical characteristics of planets in the habitable zones around bright, nearby stars?**
2. **What is the architecture of planetary systems?**
3. **When, how and in what environments are planets formed?**

Astrometric planet search recommended by the Exoplanet Task Force (AAAC 2008) (Advisory to the upcoming Decadal Survey)

"The ***only*** technique appropriate to survey the nearest hundred or so bright sun-like stars in the mid-term is *space-based astrometry*, and this is one cornerstone of the Task Force recommendations."

A Versatile μas Astrometry Mission in 2010-2020

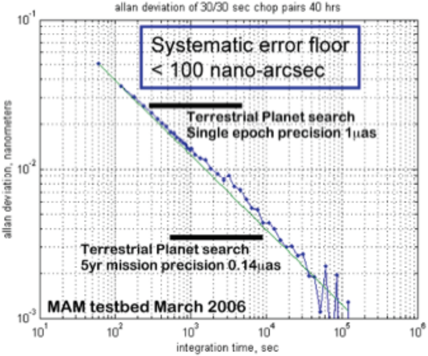
- Conclusion #1 was that, in whatever form it is realized, a μas capable astrometry mission will address the highest priority science programs, however...
- Conclusion #2: SIM-Based Architecture Ready to Deploy a Versatile μas astrometry mission *now*!
  - 1980, 1990, 2000 decadal survey
  - 30 years tech development
  - Several $\times$ \$100M invested
  - All Technological Milestones Met *or exceeded (6/8)!*

Why is SIM-Lite Less Expensive Than SIM?

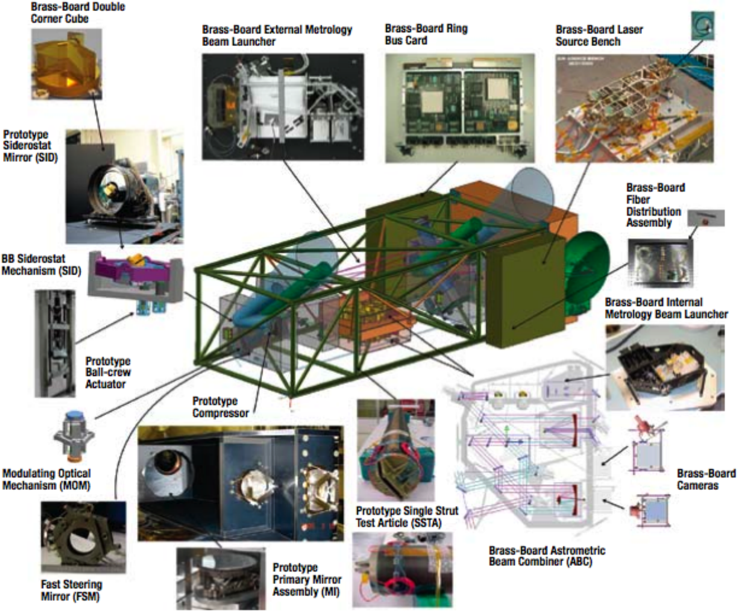
	SIM	SIM-Lite
Science Baseline	9m	6m
Guide Baseline	6m	4.5m
Guide Interferometers	2	1
Guide Telescopes	0	1

MAM Testbed Results:

- Photon-noise limited $< 0.035\mu\mathrm{as}$
- Noise floor times SNR needed (~ 5.8) is much less than 0.3 $\mu\mathrm{as}$ Earth around a Sun-like star at 10pc.
- White Noise Averages $\sqrt{N}$, the $\mu\mathrm{as}$ mission detects sub-$\mu\mathrm{as}$ signals



All technology milestones met, *Exceeded on 6/8*


Brass-Board Double Corner Cube
Brass-Board External Metrology Beam Launcher
Brass-Board Ring Bus Card
Brass-Board Laser Source Bench
Prototype Siderostat Mirror (SID)
Brass-Board Fiber Distribution Assembly
BB Siderostat Mechanism (SID)
Brass-Board Internal Metrology Beam Launcher
Prototype Ball-crew Actuator
Prototype Compressor
Modulating Optical Mechanism (MOM)
Prototype Single Strut Test Article (SSTA)
Brass-Board Cameras
Brass-Board Astrometric Beam Combiner (ABC)
Fast Steering Mirror (FSM)
Prototype Primary Mirror Assembly (MI)

Astrometry and RV

- Can RV Find Earth's Without Astrometry?
  - Quasi-periodic Astrophysical Noise
  - Our Sun, Sunspots (other sources also exist)
    Spot area 10^{-3}, Sun at 10 pc

	Astrometry	RV
Spot Bias	0.25 μas	1 m/s
1AU Earth	0.3 μas	0.1 m/s

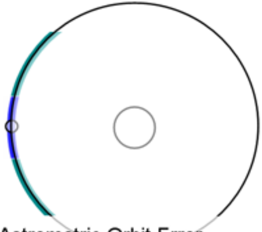
  - Need *Year-long* stability, *not* month-long!
  - Sun typical to quiet, very few slightly more stable, But $10\times$?
    (Hall, Henry, et al, *AJ* in press)
- Can RV Help Astrometry?
  - Yes! Longer Time Coverage
  - Very helpful in Double Blind Study to Identify Long-Period Jupiters
  - Third Dimension Aids in System Geometry Key Science

Astrometry and Imaging I

Does Astrometry Make Imaging More Efficient?

- Yes, Scientifically: Characterize Mass (Most Important Property)
- Yes, Where To Look: Identify specific targets
- Yes, When To Look:

- SNR ~ 6, astrometric orbit:
  - Period $\pm 3\%$, a $\sim 3\%$
  - Phase $\sqrt{2}/SNR \sim 0.25$ rad
- Extrapolate to later date:
  - $\sigma_\phi(T) \sim \mathrm{RSS}(0.25,\ T \times 0.03 \times 2\pi)$
  - $\sigma_\phi \sim 1$ rad ($T = 5$ yrs)
- When to look
  - $\sigma_\phi(0) = \pm 14$ days; $\quad \sigma_\phi(5) = \pm 58$ days



Astrometric Orbit Error
Blue – mid-epoch (σ_r~0.03 AU),
(σ_θ ~0.25 radians)
Green – 5 yrs after mid-epoch

Astrometric orbit +1 image 5 years later, greatly decreases the σ_ϕ ($\sim 10\times$), mostly from the 5 year span.

Astrometry and Imaging II

What Can Direct Imaging Do Without Astrometry?

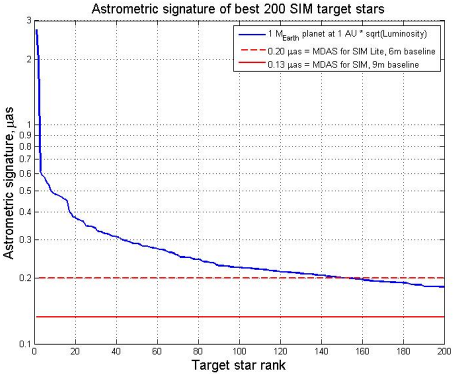
See a dot in a sea of speckles, is that enough? No!

- 1 image at 1 epoch says nothing about orbit.
- Brightness changes by $\sim 4\times$ depending on phase. 2 dots at 2 epochs, same brightness: may be different planets!
- A 4AU Neptune bright as 1AU Earth. Brightness ambiguous.
- Orbits track which dot is which.
- Must image $\sim 90\%$ of stars without Earths.
- Must visit those 90% many times (12-20), because other planets can initially mimic Earth-HZ.

Astrometry and Imaging III

- For the 10% with Earth-HZ:
  - Without Astrometry: Give up after 12 images of the star and no images of the Earth-like planet?
  - With Astrometry, need few images to get 1st image of the planet, but confident its there.
- What Form Should the Direct Imaging Mission Take?
  - Without Astrometry: Guess at Mission Requirements, Make Overcapable (and more expensive) to Ensure Success
  - With Astrometry: Specific targets, their properties, known; minimum mission requirements known, optimize for targets
- Don't Forget:
  The Mass (Most Important Property To Characterize)
- Of course, while astrometry does some characterization and can completely address some science programs, for other science cases (e.g. life), astrometry needs imaging just as much as imaging needs astrometry!

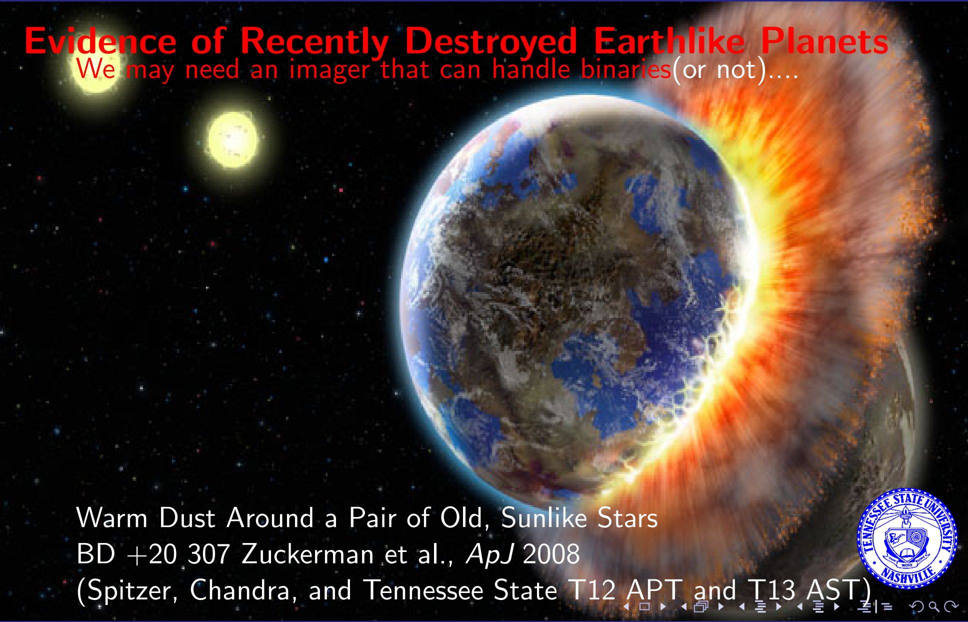
Synergy With Direct Imaging: Real Targets



- Each star considered viable for direct imaging detected planets.
- Some imaging methods don't work for some stars: examples:
  - Some TPF-C concepts work with binaries, others (TPF-O) may not.
  - TPF-I at mid-IR may give better contrast for extremely luminous stars.
- Knowledge of specific imaging targets aids in deciding imaging design.

Evidence of Recently Destroyed Earthlike Planets

We may need an imager that can handle binaries(or not)....



Warm Dust Around a Pair of Old, Sunlike Stars

BD +20 307 Zuckerman et al., *ApJ* 2008

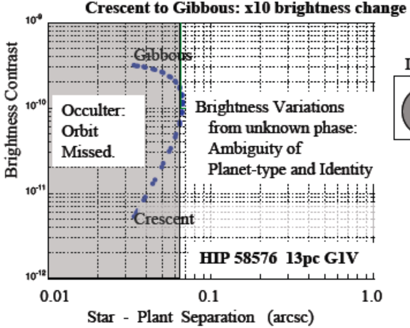
(Spitzer, Chandra, and Tennessee State T12 APT and T13 AST)

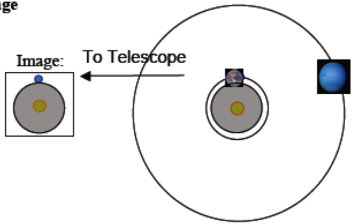
Other Applications of Astrometry in 2010-2020

- Other astrometry programs can do unique secondary exoplanet science in 2010-2020, but none can do the highest priority topics covered by the micro-arcsecond mission. The committee finds that these are worth being pursued, but *only if doing so will not delay the deployment of the highest priority microarcsecond astrometry mission.*
- *Gaia*: little impact on the μas astrometry mission
- Many giant planets around many stars
- Infrared Astrometry: Ground-based or small space mission
- Masses for Known Planets
- Theory

Imaging: Earth-Neptune Ambiguity

- Astrometry: Distinguishes Earths from Ice Giants: x17 in Mass.
  - Brightness and color map poorly to planet type.
- Imaging: Can lose identity of planets with multiple planets winking in and out of occulting mask, changing brightness by x10 with phase.
- Astrometry removes ambiguities; orbit distance establishes habitability.





Neptunes vs. Earths: Both Pale Blue Dots

Neptune: 4X Earth diam., but similar brightness & color at ~4 AU